A Method of Tracking the White-Line Course Using Image Processing for an Autonomously Guided Vehicle*

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In this paper, the method by which an autonomously guided vehicle tracks a white-line course using image processing is described. There are three peculiarities in this method. The first is that the input images of the white-line course are all segmented and are treated by serial pattern numbers. The second is that each input image has the output value of the steering calculated in advance and all the output tables according to the input images are stacked in the data files. The third is that the path is approximately tracked by connecting the several arcs which occur. We confirmed the effects of this method using a simulator which replicated the motion of an autonomously guided vehicle.

Key Words: Image Processing, Vehicle, Autonomous Guide, Factory Automation, Pattern Recognition, Motion

1. Introduction

Recently, factory automation technology has been progressing remarkably. Many kinds of robots and automatic machines have been applied in several positions of factory production lines. In addition, autonomously guided vehicles are indispensable for further automation development. New types of autonomously guided vehicles which are more flexible and have a higher degree of intelligence are desired.⁽¹⁾

The guided methods of autonomous vehicles are classified into the following two groups: 1) a track type, including an electromagnetic induction system, which runs along the magnetic field generated from the electric current of an underground cable, and an optical induction system, which runs along a white line or a metal foil tape detected by a photosensor alley. 2) The second is a program-running system, which is trackless, and runs along the preinput course by way of a measuring wheel rotation or gyroscope⁽²⁾.

The former systems using track courses are more popular than the latter system.

However, in spite of its popularity, the electromagnetic induction system has two problems. First, the cost of burying a induction cable underground is high, and second, it is difficult to change the initial course. On the other hand, the course of the optical induction system can be changed easily but does not allow high running speed. Thus, neither of these systems is fully satisfactory⁽³⁾⁽⁴⁾.

Many studies of an intelligent vehicle which uses an eye system have been performed. Various techniques have been used, such as that in which the vehicle is run by recognizing graphic marks and following a specific command⁽⁵⁾, or the vehicle is programmed to match a map template to an input image⁽⁶⁾, or that in which the vehicle avoids obstacles by recognizing them through stereoscopic vision⁽⁷⁾. Recent systems, however, are not as concerned with the running speed and stability since the processing of abundant image information takes much time and money and an optimum steering technique has not been introduced.

In this paper, a recommended running system is

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introduced. This system uses image processing to improve the problems of the autonomously guided vehicles on a track-type system by forming a white-line course which can be easily changed. This report outlines the actual movement of a test vehicle using a scale of 1 to 10 for confirmation.

2. Principle

To apply image processing to the control of an autonomously guided vehicle, various types of processing systems are assumed. This paper describes a system which uses the constant processing of a picture of a static white line taken by a TV camera on the vehicle. The moving mechanism of the TV camera (rotation, for example) is not employed in the test because of the forward, backward and turning movements by the vehicle. The TV camera itself remains stationary. Moreover, the road surface is flat and smooth (the road surface inside a factory, for example), and neither the crossing nor the branching of the white line are taken into consideration.

Figure 1 shows the setting of the TV camera. The camera is fixed to the center front of the vehicle in order to photograph the white line directly in front of the vehicle. Step 1 to step 4 in Fig. 2 are processed into the input image P_n which is taken at the time T_n to run the vehicle. At the time T_{n+1} when the same processing steps are carried out, the next image P_{n+1}

Fig. 1 An autonomously guided vehicle using the eye system

Fig. 2 Flow chart showing processing sequence

is taken. Repeated processing of each individual step is outlined in the following section.

2.1 Extraction of feature points on the course

In step 1, an extraction of the feature points representing the white line is made. The input image P_n is a binary of the picture resolution, including picture elements of 256×256 . Here, the white line is made binary so that it has a brightness value=1 (white pixel) and the road surface has brightness value=0 (black pixel). As shown in Fig. 3, four check lines l_1 to l_4 are set on the picture to calculate the gravity centers G_{i1} to G_{i4} of the white pixels on each check line against the image of the white line. These four gravity centers are regarded as the feature points representing the white line in an input image. Not every input picture image has four at maximum and one at minimum. If a white line does not exist on a picture, the feature point is zero. In this case, the vehicle should not be running along the white-line course.

2.2 Calculation of pattern value

In step 2, pattern values of the feature points obtained in step 1 are calculated. First, an input image is divided into eight areas, a to h, as shown in Fig. 3 and it is checked to determine which area the feature points belong on the check lines l_1 to l_4 , respectively.

Considering that no white line exists on any check line, the value of the area of a split number plus 1 is the case number per check line. The value is formed by multiplying by the power of the check line ($9 \times 9 \times 9 \times 9 = 6561$ types in an input image). This indicates that the white line in an input image can be treated in any case by a finite pattern value corresponding to the uniformity of this system.

2.3 Outline of the running route

In step 3, the running route for a vehicle meeting a white line in an input image is obtained. To decide a running route on a real plane, the feature points of the course are transformed projectively from the coordinate system of the image (x, y) , as illustrated in Fig. 4, to the coordinate system of a real plane (X, Y) . Here, the following equations are formed:

$$X = \frac{(x - k \cdot F \cdot \tan(-\theta)) \cdot H}{\{k \cdot F + x \cdot \tan(-\theta)\} + p} \quad (1)$$

Fig. 3 Check lines, feature points and image division

$$Y = -y \cdot \sec(-\theta) \cdot H / \{k \cdot F + x \cdot \tan(-\theta)\} \quad (2)$$

where

X : x -axis of the coordinate system of a real plane

Y : y -axis of the coordinate system of a real plane

x : x -axis of the coordinate system of the image

y : y -axis of the coordinate system of the image

θ : Angle of the TV camera

k : Constant of magnification setting

F : Focal length of the TV camera

H : Height of the center of the TV camera lens

p : Distance between the center of the vehicle and setting point of the TV camera

The coordinate system of a real plane has its original point in the center of the vehicle, on which the running direction is the X -axis and the lateral direction is the Y -axis. In the coordinate system of the image, the center of the picture is the original point allowing the vertical direction to be the x -axis and the lateral direction the y -axis.

For the group of feature points G_{i1} to G_{i4} calculated by the coordinate system of the image, the above projective transformation is performed. Thus, coordinates of the group of featuring points G_{r1} to G_{r4} in the coordinate system of a real plane are calculated.

Next, for the group of feature points G_{r1} to G_{r4} and the center of a vehicle (original point) in the coordinate system of a real plane, a least squares approximation is performed by the following cubic curve to obtain the coefficients, a and b ,

$$Y = X^2 \cdot (a \cdot X + b) \quad (3)$$

The cubic curve of Eq. (3) must pass through the original point (center of vehicle) and must have an extreme value on the original point. Accordingly, it coincides with the movement of the vehicle always having a velocity component only in the X -axis direction on the original point (attitude angle $\theta_0 = 0$), and suits a smooth route connection when changing over the picture. This curve is, then, regarded as a running route of the vehicle for the input image P_n .

Fig. 4 Real and image planes

2.4 Steering output

In step 4, a steering output is given to run a vehicle on the cubic curve (a running route) obtained in the previous section. As shown in Fig. 5, when a vehicle runs on the cubic curve $f(x)$, an inverse tangential value of the differential coefficient of the curve on X_n and an attitude angle θ_n are always coincident. Equation (4) indicates this relation:

$$\phi_n = \tan^{-1}(f'(x)) \quad (4)$$

Okada reports⁽⁸⁾ on the basic theory of maneuverability and stability by using a two-wheeled model (an autobicycle, for example) which substitutes a four-wheeled model (an automobile, for example). Further more, in this technique, with the condition that the cornering coefficients of the front and rear wheels are fixed, a two-wheeled model which is substituted as the vehicle is examined. The basic action becomes, accordingly, a steady circular turn, as indicated by Eqs. (5) and (6). As shown in Fig. 6, the variation of an attitude angle by steering in ξ and running at speed V is $\Delta\phi$, and the radius of the turning circle is R .

$$\Delta\phi = V \cdot \xi \cdot \Delta t / L \quad (5)$$

$$R = L / \xi \quad (6)$$

where

$\Delta\phi$: Variation of attitude angle after Δt second

ξ : Steering angle

R : Radius of steady turning circle

Δt : Time

V : Speed of the vehicle

L : Wheel base of the vehicle

Fig. 5 Relations between the attitude angle of a vehicle and values of differential coefficients of the curve

Fig. 6 A steady circular turn

In this technique, a unit moving a distance $\Delta l (= V \cdot \Delta t)$ is set previously. The steering is controlled every time (Δt sec) the vehicle is required to move this distance. Let us now think of a case in which a vehicle is moved from a point $Q_n(X_n, f(X_n))$ to another point $Q_{n+1}(X_{n+1}, f(X_{n+1}))$ on the curve at a speed of V during Δt seconds. The distance S between Q_n and Q_{n+1} on the cubic curve is expressed by

$$S = \int_{X_n}^{X_{n+1}} \sqrt{1 + (f'(X))^2} dx \quad (7)$$

Letting $S=l$ and obtaining a coordinate of Q_{n+1} being advanced by S from Q_n , a circle in contact with two points is determined. That is, a distance S on the cubic curve $f(X)$ is approximated by a circular arc of radius R . By providing steering output corresponding to this radius R for every distance S , a vehicle continues to repeat the basic action as a steady circular turn, changing the radius R every Δt seconds (changing the steering amount) where a cubic curve can be realized approximately according to the connection of the circular arc of S in the arc length.

In addition, the length of each circular arc corresponds to a variation of attitude angle $\Delta\phi$ from the attitude angle ϕ on Q_n of a vehicle to the attitude angle ϕ_{n+1} on Q_{n+1} so that the steering output ξ is obtained from Eq. (8).

$$\xi_n = \{ \tan^{-1}\{f'(x_{n+1})\} - \tan^{-1}\{f'(x_n)\} \} \cdot L / (V \cdot \Delta t) \quad (n=0, 1, 2, 3, \dots m) \quad (8)$$

2.5 Acceleration of processing

As mentioned in section 2.3, the appearance of a white line on a picture, namely a pattern, provides a finite number according to the divisions of the picture. Moreover, cubic curves determined from those input images (patterns) are also finite (6561 types in 8×4 divisions, for example).

Then, a fixed moving amount ($n \times \Delta l$, $n=0, 1, 2, 3, \dots m$) of the steering output value for each input pattern is calculated to form the steering output table. By registering a group of steering output tables, judging the pattern of the white line in an input image and immediately retrieving a table of patterns to provide the steering output, the processing is accelerated.

Fig. 7 A tester which simulates the movement of a vehicle

3. Examination by Tester

To examine the effectiveness of this technique, a tester which realizes the movement of a vehicle was used. The results are as follows:

3.1 Outline of tester

The tester is shown in Fig. 7. On this tester, the setting of the TV camera corresponds to the vehicle and the belt to the road surface. The TV camera has two degrees of freedom: lateral and rotational. The belt painted with a white line moves according to the acceleration speed. On this tester, the vehicle does not move on top of the road surface but rather the road surface moves under the vehicle.

In this technique, a vehicle is substituted with a two-wheeled model, and the basic action of the vehicle can be realized sufficiently by controlling only three shafts of the tester. Movement of a vehicle equipped with a visual apparatus and that of the tester are illustrated conceptually in Fig. 8. The figure indicates that the input images of a vehicle and the tester are coincident when running on the same white line.

For the testing sequence, the white line was 15 cm in width, which is the same width as that of the real center line on a road. The belt surface was delustered by coloring it black in order to avoid any disturbance caused by reflections. The maximum speed of the vehicle is set at 10 km/h, the same as that of the electromagnetic induction system, and the processing capacity of the image is set to be 400 m sec a picture, namely 2.5 frames a second according to the performance of the tester used. The vehicle travels 1.1 m at

Fig. 8 A comparison between vehicle action and a tester

Table 1 Setting conditions

Focal length		16.0 mm
Field of view	Horizontal	30.0 deg
	Vertical	23.0 deg
TV camera angle		106.0 deg
TV camera height		50.0 cm
Wheel base of vehicle		10.0 cm
Velocity of vehicle		-30.0~+30.0 deg
Steering output cycle		200.0 msec
Image processing		2.5 frames/sec
Resolution of an image		256x256 pixels

Fig. 9 The running loci of a vehicle to a straight line

10 km/h during the processing of one frame of the picture. As a safety feature, a stop signal is required before a vehicle reaches the point when detecting an abnormality of a front input image. Taking a 50% margin of error, accordingly, a vision is fixed at a distance of 1.7 m from the front. The setting conditions of the TV camera and devices are shown in Table 1. This tester handles a model down to 1/10 of the actual vehicle to meet the limited space of the laboratory.

3.2 Linear returning characteristics

It became clear that a vehicle placed 100 cm from the straight course could return to the course smoothly. The running loci for 15 and 8 divisions on a picture are illustrated in Fig. 9. This figure indicates that a vehicle returns to the white line smoothly at about 5 m ahead. After returning to the course, the loci of 15 divisions is stable, while that with 8 divisions drifts steadily. The amount of this drift is, however, as small as about 5 cm, and is not a serious problem.

3.3 Number of divisions on a picture and running characteristics

To confirm the influence of the number of divisions of an input image to a running vehicle, a white line in contact with a semi circle of radius R , as referred to in Fig. 10, was introduced. For three types of divisions on an input image, 4, 8 and 16, the critical corner radius values for possible running at 10 km/h obtained in the tests are shown in Table 2. Moreover, the critical corner radius values enabling the run by

Table 2 Critical corner radius values for possible running at the vehicle velocity of 10 km/h

Image division number	4	8	16
Vehicle simulator (tester)		14m	14m
Result of calculation	16m	14m	12m

Fig. 10 The white-line course in contact with half circles of radius R

the static calculation ignoring the dynamic characteristics are also shown together. Theoretically, it is clear that running is possible by the corner radius value becoming lower as the number of divisions becomes higher. This could be caused by the fact that the higher the number of divisions, the smaller the drift which occurs, as shown in Fig. 9. However, there was no difference found between 8 divisions and 16 divisions on the tester, where the critical running radius value for both was 14 m, and no running was available by 4 divisions. It can be assumed that the characteristic does not appear, owing to a delayed response time of the tester.

4. Conclusions

A new technique to realize running of an automatic vehicle on a white line by processing pictures was discussed. Features of this system are:

1. Movement of the vehicle is smooth

Macroscopically, the locus of a vehicle is a smooth contact of cubic curves while microscopically, each cubic curve is a smooth contact of a circular arc. Thus, a sharp steering output does not exist. Consequently, a smooth movement is available even when the timing of the steering output is as high as 200 msec.

2. Processing is quick

Steering data of all patterns of the images of input white line are kept. Judgement is, accordingly, only exercised when an image is input, but a successive calculation of the approximation or output value is not required. The above two items are considered. In addition, as the secondary effects:

(1) Running corresponding to the degree of running stability required can be set. (Running characteristics can be changed by setting the number of divisions on the picture.)

(2) If a vehicle runs off the course owing to external factors, the vehicle returns quickly to the course when the white line exists within an input image. (In the electromagnetic induction system, a vehicle is unable to return to its course if it runs 10 cm or further from the course.)

(3) If a new image is misphotographed due to a disturbance, a vehicle can run on the running route (cubic curve) obtained from the last image. Thus, it is difficult to deviate from the course.

As stated above, this technique has very desirable features for practical use. A technique introducing the approximation by a curve of higher order as an improvement of this technique will be considered. There is, however, a problem that an approximate curve (running course) does not always pass through every feature point representing the white line at the approximation of the n -dimensional function. We think that the thinking function or the Hermit interpolation will be effective to solve this problem. And we should confirm that how big an increase of the running characteristics can be availed by using these functions. Further more, a theme to establish a technique for practical use, to cope speedily and effectively with

contamination and lack of a white line, remains unsolved.

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